Earth and Planetary Science Letters 386 (2014) 1–9

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

A new constraint on the size of Heinrich Events from an iceberg/sediment model

William H.G. Roberts [a], Paul J. Valdes [a], Antony J. Payne [b]

[a] BRIDGE, School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, United Kingdom
[b] Bristol Glaciology Centre, School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, United Kingdom

ARTICLE INFO

Article history:
Received 5 March 2013
Received in revised form 7 October 2013
Accepted 9 October 2013
Available online 18 November 2013
Editor: J. Lynch-Stieglitz

Keywords:
Heinrich events
Heinrich layers
iceberg modelling

ABSTRACT

Heinrich Layers, anomalously thick layers of ice-borne sediment in the North Atlantic ocean, have long been associated with abrupt climate changes in glacial times. However, there is still no consensus on either the exact amount of ice needed to transport this sediment or how such a large volume of ice could be produced. Using an iceberg model that includes sediment, we simulate the delivery of sediment to the North Atlantic during such an event. Our model assumes that sediment is uniformly distributed within the ice with a concentration of 4%. Unlike sediment models which assume that the sediment lies in a single layer, this model can carry sediment all the way from the western to the eastern North Atlantic. We use a variety of different estimates for the total volume of ice released to model the sediment layer thickness and we show that to best fit the observations 60×10^4 km^3 (with a plausible range of $30–120 \times 10^4$ km^3) of ice needs to be released. This is equivalent to a 0.04 Sv (10^6 m^3 s^{-1}, with a plausible range of 0.02–0.08 Sv) release of freshwater over the 500 yr of a typical Heinrich Event. This is a smaller flux of water than is required to show a significant impact on the global climate in most current "state of the art" GCMs.

1. Introduction

A number of sediment cores (e.g. Heinrich, 1988; Hemming, 2004 and references therein) taken from the North Atlantic have identified so-called Heinrich Layers (HL), layers of sediment with an anomalously high fraction of ice-raft debris (IRD). The provenance of this IRD is predominantly the Laurentide Ice Sheet (LIS, Broecker et al., 1992) although there is also evidence for some IRD coming from the Fennoscandian Ice Sheet (Grousset et al., 1993), as well as the Greenland and British Ice Sheets (Scourse et al., 2009). This IRD is found in the region of the IRD belt (Ruddiman, 1977), a zonal strip of the North Atlantic between 40 °N to 55 °N. The thickness of the IRD associated with HL varies amongst the cores but generally averages around 10–15 cm, with thicker layers of tens of centimetres of sediment near the Labrador Sea, and thinner layers of a few centimetres on the eastern side of the Atlantic basin near the Iberian Peninsula (Hemming et al., 1998). In order to deposit such thick layers of sediment over such a wide area (the area of the IRD belt is of the order of 10^6 km^2) huge numbers of sediment carrying icebergs must have been released. This surge of icebergs, or Heinrich Event (HE), is thought to be the result of an abrupt collapse of the LIS (Broecker et al., 1992), the collapse of an ice shelf in the Davis Strait fed by the LIS (Hulbe, 1997), or some combination of the two (Álvarez Solas et al., 2011). Although a number of different ice sheet models (Marshall and Clarke, 1997; Hulbe, 1997; MacAyeal, 1993) have estimated the volume of ice produced by such collapses (other models have simulated HE, Calov and Ganopolski, 2002; Álvarez Solas et al., 2011 but not reported the total volume of ice released), there has been no effort to reconcile how the volume of ice released might translate into a sediment layer thickness. More disturbingly, other approaches to calculating the volume of ice in an HE (Hemming, 2004; Levine and Bigg, 2008; Roche et al., 2004) give results that differ by almost two orders of magnitude. These results are summarised in Table 1. Such a wide variety of estimates for the ice volume released in an HE has serious implications for climate modellers charged with the task of understanding their effect on the climate, since without an understanding of the size of the forcing it is difficult to estimate the size of the response.

The prevailing view is that the flux of ice released by an HE leads to a freshwater flux into the North Atlantic ocean that causes an abrupt change in the ocean's deep Meridional Overturning Circulation (MOC, Broecker, 1994; Ganopolski and Rahmstorf, 2001). It is then argued that this change in the MOC allows the effects of the HE, which is a local feature in the North Atlantic, to be felt globally. However, the fluxes of freshwater equivalent to the volume of ice produced by the different HE models can force a wide range of MOC responses in Global Climate Models (GCMs), from a total collapse to a marginal slowdown, each of which has a quite different effect on the models' climate (Ganopolski and Rahm-

0012-821X/$ – see front matter
http://dx.doi.org/10.1016/j.epsl.2013.10.020

Table 1
Table of ice volumes, equivalent freshwater fluxes and fit to observed data for all ice volume estimates presented in Fig. 3. Where it is required a timescale of 500 yr is used to calculate either a total volume or volume flux for each Heinrich Event (Hemming (b) assumes a timescale of 1 yr). Those values that use this timescale are highlighted in *italics*.

Model	Total ice volume (10^4 km^3)	Freshwater flux (Sv, 10^6 m^3 s^{-1})	RMS error	Comment
MacAyeal (1993)	125	*0.08*	17.2	Ice Sheet Models
Dowdeswell et al. (1995)	*27.0*	0.02	14.6	
Marshall and Clarke (1997)	24.2	0.10*	13.5	
Hulbe (1997)	75.0	*0.05*	11.4	
Hemming (2004) a/b	*946/3*	0.6/1.0	186/16.5	Isotope estimates
Roche et al. (2004)	85.8	0.29	12.2	
Levine and Bigg (2008)	649	*0.41*	144	Precipitation balance
This study	60	*0.04*	10.9	Iceberg/sediment model

* We note that the volume flux calculated by Marshall and Clarke (1997) is the peak volume flux from the model, which is larger than the average volume flux over the whole event.

storf, 2001; Stouffer et al., 2006; Otto-Bliesner and Brady, 2010; Kageyama et al., 2013).

Therefore if we are to better understand what effect HE may have on the climate and test the ability of GCMs to accurately model the climate's response to HE we must better constrain this volume of ice. In this study we demonstrate a new way to constrain the volume of ice that is released during an HE: to directly model the HL thickness.

This paper will proceed as follows: Section 2 describes the models that we use and details some of the assumptions that we make. Section 3 presents results from the model. We show, in Section 3.1, the spatial pattern of sediment that would result from a release of icebergs from Hudson Strait during the last glacial period, we then show, in Section 3.2, how deep an HL is implied by previous studies of HE and present an estimate for the optimal volume of ice that is needed to explain the observed thickness of HL. In Section 4, we discuss in detail some of the assumptions that were made in the model, and what effect they may have upon our results. We conclude in Section 5 by setting these results in the wider context of other HE studies and highlighting what they mean for modelling of the climatic signal of HE.

2. Model

In order to model the thickness of the HL we use a two step modelling process. First we use an iceberg trajectory model (Bigg et al., 1997) to simulate the tracks, sizes and melt volumes of icebergs released during an HE. Then, by simulating the release of sediment from the icebergs, we compute the thickness of the HL that would result from the deposition of sediment as the icebergs melt. Because the thickness of the HL depends upon the volume of ice released during the HE, we calculate the thickness of the HL that arise from different estimates of HE ice volume. We then constrain the ice volume estimates by finding the best fit of simulated HL thickness to the observed layer thickness. A similar procedure was followed by Matsumoto (1997), however the HL thickness was not estimated in this study.

The iceberg model calculates the time evolution of iceberg sizes and tracks. These are determined by the winds, ocean currents and sea surface temperature. Winds and currents, along with the Coriolis force and drag terms, determine the trajectories of the icebergs. The evolution of their size is determined predominantly by wave erosion on their sides and turbulent heat transfer, hence melt, beneath them. The model has been shown to replicate the distribution of modern day icebergs in both the Arctic (Bigg et al., 1997) and Antarctic (Gladstone et al., 2001). In order to model iceberg trajectories during HE we use forcing fields from the Last Glacial Maximum (LGM).

There is a lack of sufficiently detailed observations of the LGM which means that we must derive the forcing fields from GCM simulations. We use a steady state simulation of the LGM, neglecting any interaction between the melting of the icebergs and the climate. The melting of the icebergs would obviously give a freshwater forcing to the model which could potentially alter the model's LGM climate.

We use a version of the GCM FAMOUS (a low resolution version of HadCM3; Jones, 2003) that optimises the model's fit to both the present day and LGM climates (Gregoire et al., 2011). The SST, wind and current data used to force the iceberg model are derived from one of an ensemble of FAMOUS model realisations described by Gregoire et al. (2011). In these runs a number of model parameters were varied and the skill of the resulting model realisation compared to a number of different observational datasets of both the present day and LGM. All models have a Meridional Overturning Circulation (MOC) whose strength varies between 12 and 19 Sv. This is within the present day observations of 18 ± 3–5 Sv (Talley et al., 2003). All models predict a cooling of global temperature at the LGM with a range of 4.6–6.2 °C. This range is comparable to estimates of LGM cooling from the PMIP2 multi-model ensemble (Braconnot et al., 2007). At the LGM the change in the MOC covers the gamut of possible responses from strengthening to weakening and deepening to shoaling. However, in none of the models is the difference between the present day and LGM MOC larger than ±4 Sv. Some of the models are in agreement with the observations (Lynch-Stieglitz et al., 2007) that show that although the LGM MOC was mostly likely different to today's, with a slight shoaling and possible weakening, it was not completely absent.

The particular version of the model used in this study is one which fits the present day observed wind and currents in the North Atlantic best. These variables were used for the optimisation as they are the most important for determining the trajectories of the icebergs. To force the icebergs we use a simulation of the LGM from this model. We show, in Fig. 1, annual mean sea surface temperature (SST), wind stress and surface currents, which are the iceberg model forcing fields. It is important to note however, that in all iceberg model runs the forcing fields include the annual cycle. There would in nature be some interaction between the melting icebergs and the climate. This interaction is potentially important (e.g. Levine and Bigg, 2008; Jongma et al., 2012), however we neglect it because we have no *a priori* knowledge of how large an effect it could be. Furthermore, an examination of idealised experiments of FAMOUS imposing an arbitrary 1.0 Sv freshwater flux to the North Atlantic, not shown, shows that the iceberg forcing fields, and the resulting iceberg trajectories, are not significantly al-